ADAPTIVE MEASUREMENT INTERVALS FOR HANDOFFS

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ABSTRACT

As cells become smaller and, consequently, handoffs more frequent, it becomes increasingly important to base the handoff decisions on as good information as possible. The purpose of this paper is to exploit the information in signal strength measurements to improve the quality of the handoff decisions.

As a vehicle moves, the signal strength changes due to (at least) three different phenomena:

1. Distance from base station.
2. Slow fading -- shadow or lognormal fading.
3. Fast fading -- Rayleigh fading.

The fluctuations due to slow and fast fading are usually considered as noise in this decision making process. This leads to the following tradeoff problem for the averaging interval for the signal strength measurements. If the interval is too short, the fading fluctuations are not sufficiently smoothed out. If the interval is too long, the handoff mechanism is too sluggish. With this tradeoff in mind, we present a method to adaptively change the averaging interval. The method is based on estimating the maximum Doppler frequency, the key to the tradeoff.

1. Introduction

As cells become smaller and, consequently, handoffs more frequent, it becomes increasingly important to base the handoff decisions on as good information as possible. The purpose of this paper is to exploit the information inherent in signal strength measurements to improve the quality of the handoff decisions. We seek to obtain useful information from signal strength variations which are normally considered only as nuisances.

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2. Slow fading -- shadow or lognormal fading.
3. Fast fading -- Rayleigh fading.

The decision for handoff is (or should be) primarily dependent on the distance dependence (although severe shadowing may dictate a handoff). The fluctuations due to slow and fast fading are usually considered as noise in this decision making process. This leads to the following tradeoff problem for the averaging interval for the signal strength measurements. If the interval is too short, the fading fluctuations are not sufficiently smoothed out. If the interval is too long, the handoff mechanism is too sluggish. In [1], this tradeoff is quantified. We show how to adaptively choose the averaging interval. The adaptation uses information already available in the signal strength measurements in a simple manner.

The time scale for the Rayleigh fading depends on the maximum Doppler frequency (which is proportional to vehicle velocity). It would be expected that the time scale for the shadow fading should also depend on vehicle velocity by virtue of its distance dependence. In fact, Ref. 2 shows a correlation function for the shadow fading that depends on distance. Thus, for both the fast and slow fading, the key to the averaging interval is vehicle velocity or its proportional surrogate, maximum Doppler frequency. Our approach to the adaptive averaging interval is, thus, through estimating the maximum Doppler frequency.

The problem being discussed is to be distinguished from that addressed in [1] (also see Section 13.3.1 of [3]). In that reference, an averaging interval is being sought which will average out the effect of the Rayleigh fluctuations. By contrast, we wish to exploit the Rayleigh fluctuations themselves to obtain information about the propagation environment and *then* use that information to determine the averaging interval. To further put our investigation into perspective, we are considering here an *ideal* Rayleigh fading environment. Further analysis will treat other realistic factors. One such factor is the distinction between signal strength and C/I measurements (see [3], Section 9.1.2, in this regard). Furthermore, it should be recognized that other measures (e.g., bit error rate) are candidates for handover triggers (either in conjunction with, or instead of, signal strength). The present study should help in comparative evaluations of these measures by indicating how information inherent in the measures can be further exploited.

There are a number of other considerations in handover decisions besides averaging intervals (see, e.g., [4]). It should also be observed that the three factors above need to be considered in power control measurements. In [5], the Rayleigh fluctuations are averaged out, while in [6], the DS/CDMA power control responds to the Rayleigh fluctuations (it needs to respond to *relatively slow* Rayleigh fading because the combination of interleaving and coding then becomes ineffective in smoothing out the fading fluctuations; see [6]).

The paper is organized as follows. In Section 2 the averaging interval tradeoff is discussed. Section 3 shows a basis for choosing the averaging interval with information available in the measurements. Error estimates are given in Section 4. Adaptive use of this information is considered in Section 5. Comparison of our approach for estimating maximum Doppler frequency to some approaches in the literature is given in Section 6. Concluding remarks are given in Section 7.

2. *The Averaging Interval Tradeoff*

In [1], the standard deviation of time averaged Rayleigh faded signal strength measurements is derived. (Stationarity is assumed over the measurement intervals in question). This result is used in [1] to determine the minimum averaging interval for a given standard deviation of the measured power in dB. From inspection of Figure 2 of [1], the following approximation is found for the minimum averaging interval, $T(k,f_d)$ *seconds*, for an averaged measurement standard deviation of $k\ dB$ (i.e., an accuracy of $k\ dB$) and a maximum Doppler frequency of f_d (in Hz):

$$T(k,f_d) \approx \frac{20}{kf_d} \qquad \text{for } 1 \le k \le 2 \qquad (2\text{-}1)$$

Remark (2-1). The maximum Doppler frequency, f_d, equals velocity divided by wavelength, v/λ. With T a time interval, f_dT measures distance in number of wavelengths. While we shall be primarily stating results in terms of time, there is always the translation to the physically meaningful distance in number of wavelengths Thus, e.g., for an accuracy of $1\ dB$ in (2-1), 20 wavelengths must be traveled.□

The required averaging interval T decreases with f_d which is fortunately consistent with needing to make a quicker decision with faster vehicles. From (2-1), it also seen that, for a given standard deviation, the minimum averaging interval can be easily found and updated if f_d can be easily evaluated and updated.

In [1], the averaging interval tradeoff is affected by slow (lognormal) fading as well as fast (Rayleigh) fading. The specific example given in Figure 4 of [1] assumes a $0.2Hz$ maximum frequency for the spectrum of the slow fading. In [2] (Section 2), the bandwidth for the slow fading is given as proportional to vehicle velocity and, thus, proportional to f_d. Hence, f_d is the key parameter for the averaging interval taking account of both fast and slow fading.

Remark (2-2). When averaging for both slow and fast fading, the slow fading predominates. □

Remark (2-3). The proportionality between f_d and the key parameters for slow fading may have a direction-dependence, not yet investigated.□

There are various ways to estimate f_d. Some possible approaches can be based on

1. Mobile velocity (proportional to f_d through the carrier frequency).
2. Inferring f_d from level crossings using results such as in [7], Chapter 6.
3. Performing a spectrum or autocorrelation analysis and inferring f_d from the spectrum or autocorrelation.
4. Squared deviations of logarithmically compressed signal envelope (amplitude) measurements.

We shall define and develop the last option in the next section.

3. *Using Squared Deviations of Signal Strength Measurements*

The rationale for using deviations of signal envelope amplitude measurements as in Point 4 above is that, if there is a *fixed* time interval between those measurements, it would be expected that the size of the deviations would increase as the fading becomes faster, i.e., as f_d increases. We shall quantify that effect now.

Remark (3-1). Note that we are using discrete-time measurements in contrast to the continuous-time measurements analyzed in [1]. For the sample mean examined in [1], the distinctions between discrete-time and continuous-time measurements are analyzed in a straightforward manner and usually slight and not otherwise consequential (see, e.g., p. 176 of [8]). By contrast, with our use of deviations here, the time difference between successive measurements will be seen to be key to the development of the method. Note that the averaging interval for our method consists of multiples of the time between successive (individual) measurements.□

Now, define

$$V = \frac{1}{N}\sum_{i=1}^{N}(y_{i+1}-y_i)^2 \qquad (3\text{-}1)$$

where

$$y_i = 20\cdot\log_{10} x_i \qquad (3\text{-}2)$$

and x_i is the i^{th} signal envelope amplitude measurement (instantaneous, not averaged). Logarithmic compression facilitates estimation of f_d since it is not necessary to make separate measurements of the mean (as will be seen in the following). For Rayleigh fading, the expectation of V is found to be approximately

$$E(V) = 62.05\,[1-J_0^2(2\pi f_d\tau)] \qquad (3\text{-}3)$$

where τ is the time between successive signal strength measurements (and, thus, the averaging interval is $T{=}N\tau$).

For (3-3), we used the following approximation from [1]:

$$cov\,(y_{i+k}, y_i) = cov\,[y\,(t+k\tau), y\,(t)] = (5.57)^2 J_0^2(2\pi f_d k\tau) \quad (3\text{-}4)$$

It is thus seen that f_d can be inferred from V. That is, $\hat{f}_d$, the estimate of f_d, is obtained from

$$V = 62.05\,[1 - J_0^2(2\pi \hat{f}_d \tau)] \quad (3\text{-}5)$$

Remark (3-2). (3-4) is actually an upper bound for the covariance function. It was found satisfactory for its use in [1]. For use in estimating f_d, however, the estimate should be corrected based on numerical comparisons with the exact expression. The use of (3-4) (with the understanding that a correction will be made) simplifies the exposition here.□

The inference of (3-5) is most transparent when

$$2\pi f_d \tau \ll 1. \quad (3\text{-}6)$$

Then a series approximation for the Bessel function yields

$$\hat{f}_d \approx \frac{1}{\pi\tau}\sqrt{\frac{V}{124.1}} \quad (3\text{-}7)$$

Even if (3-6) does not hold, it is easy to infer f_d from V using (3-5) and we do not assume (3-6) in the analysis to follow. It should be recognized, however, that a condition like $2\pi f_d \tau < 1$ is needed for effectiveness of estimating f_d from (3-5) because of zeros of the Bessel function. This will be made evident from the error analysis of the next section. For f_d up to 100 Hz, a τ of 1 ms yields $2\pi f_d \tau < 0.628$.

4. Error Analysis

An estimate for the the variance of V is (with $z_i = y_i - E\,(y_i)$):

$$\begin{aligned}
var\,(V) &= N^{-1}\, var\,(y_{i+1} - y_i)^2 \\
&\quad + 2N^{-2}\sum_{j=1}^{N-1}(N-j)\,cov\,[(y_{i+1}-y_i)^2, (y_{i+j+1}-y_{i+j})^2] \\
&= N^{-1}\, var\,(z_{i+1}-z_i)^2 \\
&\quad + 2N^{-2}\sum_{j=1}^{N-1}(N-j)[cov\,(z_{i+1}^2, z_{i+j+1}^2) \\
&\quad -2cov\,(z_{i+1}^2, z_{i+j}z_{i+j+1}) + cov\,(z_{i+1}^2, z_{i+j}^2) \\
&\quad -2cov\,(z_i z_{i+1}, z_{i+j+1}^2) + 4cov\,(z_i z_{i+1}, z_{i+j}z_{i+j+1}) \\
&\quad -2cov\,(z_i z_{i+1}, z_{i+j}^2) + cov\,(z_i^2, z_{i+j+1}^2) \\
&\quad -2cov\,(z_i^2, z_{i+j}z_{i+j+1}) + cov\,(z_i^2, z_{i+j}^2)] \\
&\approx 8N^{-1}\,[var\,(y_i) - cov\,(y_{i+1}, y_i)]^2 \\
&\quad + 4N^{-2}\sum_{j=1}^{N-1}(N-j)\{4\,cov\,(y_i, y_{i+j})[cov\,(y_i, y_{i+j}) \\
&\quad - cov\,(y_i, y_{i+j-1}) - cov\,(y_i, y_{i+j+1})] \\
&\quad + [cov\,(y_i, y_{i+j-1}) + cov\,(y_i, y_{i+j+1})]^2\}
\end{aligned} \quad (4\text{-}1)$$

where i is arbitrary for a wide-sense stationary process and we have used (8-121) in [9]. This uses a joint Gaussian approximation for the z_i, as is commonly done in related correlation analyses (e.g., [10], p. 271).

Remark (4-1). There is also a bias in the estimate of V due to nonlinearity which, however, is not as significant as the bias due to measurement noise. We shall return to this in Section 6.□

An estimate for the relative error in $\hat{f}_d$, is given by (using (3-3) above and (5-56) of [11]):

$$\frac{\sigma(\hat{f}_d)}{f_d} \approx \frac{\sqrt{var\,(V)}}{248.2\pi f_d \tau\,|J_0(2\pi f_d \tau)\cdot J_1(2\pi f_d \tau)|} \quad (4\text{-}2)$$

Note, in particular, the unboundedness of this error estimate near zeros of the Bessel functions (J_0 has a zero at 2.4, J_1 has zeroes at 0 and 3.8). Thus, one should choose τ small enough to avoid those zeros. This confirms the comment about the size of τ at the end of the last section. For the rest of this paper, we shall assume $\tau = 1$ ms.

Numerical results for this relative error are given in Figure 1. The relative error, $\frac{\sigma(\hat{f}_d)}{f_d}$, is plotted versus the averaging interval, T (in seconds), with f_d (in Hz) as a parameter. τ is fixed at 1 ms (for the reason given in the last paragraph). The use of (3-7) facilitates interpretation of the results. From (3-7), we obtain

$$\frac{\sigma(\hat{f}_d)}{E\,(\hat{f}_d)} = \frac{\sigma(\sqrt{V})}{E\,(\sqrt{V})} \quad (4\text{-}3)$$

and, then relating the coefficient of variation of a random variable to that of its square root,

$$\frac{\sigma(\hat{f}_d)}{E\,(\hat{f}_d)} \approx \frac{1}{2}\frac{\sigma(V)}{E\,(V)} \quad (4\text{-}4)$$

Remark (4-2). The errors in Figure 1 are to be taken as *qualitative* indicators. First of all, several approximations were used to derive them (simulations indicate that they are underestimates). Secondly, measurement noise needs to be considered (see Remark (4-1)).□

5. Adaptive Measurements

The results of Section 3 indicate that the averaging interval can be done adaptively. In particular, we would like to adaptively choose the number of samples N (with τ fixed) for the sample mean S

$$S = \frac{1}{N}\sum_{i=1}^{N} y_i \quad (5\text{-}1)$$

Remark (5-1). The continuous-time version of Eq. (5-1) is examined in [1]; see Remark (3-1).□

One convenient way to facilitate that is to replace (5-1) by exponential smoothing (e.g., [12], Section 4.3) and continually adjust the weights:

$$S_{i+1} = \alpha(V_i)y_{i+1} + [1-\alpha(V_i)]S_i \quad (5\text{-}2)$$

$$V_{i+1} = \beta(V_i)(y_{i+1}-y_i)^2 + [1-\beta(V_i)]V_i \quad (5\text{-}3)$$

Here, α and β are both exponential weighting factors, each continually updated by the most recent V estimate, which is

related to f_d. The functional forms of these weighting factors are to be determined for differing situations. A general basis for the choice is as follows.

1. Given V_i, estimate f_d.
2. From f_d, determine an appropriate N for (5-1). This involves the tradeoff between estimation error and lag in the handoff algorithm response, as discussed. This tradeoff is not resolved here, requiring more work which also accounts for the combined roles of averaging interval and hysteresis (see [13], [14]).
3. Relate $\alpha(v_i)$ to $N(v_i)$. This is done by noting that, for constant α, (5-2) is equivalent to

$$S_{i+1} = (1-\alpha)\sum_{j=1}^{\infty}\alpha^j y_{i-j} \tag{5-4}$$

   so that the past sample y_{i-j} is attenuated by $(1-\alpha)\alpha^j$. By setting $(1-\alpha)\alpha^N$ equal to say, $1/e$, one can determine an an α corresponding to an N.
4. Use $\alpha(V_i)$ to update (5-2).
5. Determine $\beta(V_i)$ in a similar manner to update (5-3).

6. Relationship to Some Other Work on Doppler Estimation

In [15], techniques are given for estimating the Doppler spread parameter D, defined as

$$D = 2\sqrt{\frac{\int(\nu-\bar{\nu})^2 P(\nu)d\nu}{\int P(\nu)d\nu}} \tag{6-1}$$

where $P(\nu)$ is the power density spectrum (with respect to time) of $T(f,t)$, the received narrowband process in response to a complex sinusoid. This is a general definition of Doppler spread while we are using the specific form of maximum Doppler frequency encountered in mobile radio. Estimates of D in [15] are given in terms of derivatives. In actually calculating derivatives, finite differences would usually be used. This is explicit in [16] (specifically, Eq. (24)), where further considerations are given for estimating D. By contrast, we do not use differences as approximations for derivatives but directly exploit the property of the differences.

The accuracy of one of the approaches of [15] is considered in [17]. They consider three sources of error:

1. Noise in measurements.
2. Sampling error.
3. Finite difference approximation to derivative.

The relationship to our work is:

1. This results in a significant bias which must be incorporated into the present study.
2. Independent samples are considered in [17] while we analyzed correlated samples.
3. We do not try to approximate a derivative with finite differences, as mentioned above.

7. Concluding Remarks

We have explored the derivation of information from the signal strength variations that is useful for adaptive handover algorithms. Further work is needed to test the idealizations assumed and to use the approach discussed here (and/or others such as mentioned at the end of Section 2) in a real-time handover algorithm. The idealizations include a purely Rayleigh environment with noiseless measurements. A number of sensitivity studies are needed. Furthermore, the interactions between averaging interval and hysteresis must be considered (see [13], [14]). It will also be of interest to see how a modification of the algorithm works in an environment dominated by non-Rayleigh effects such as turning corners.

As mentioned in Section 2, f_d can also be obtained from vehicle velocity if that information is available to the handoff algorithm processing system. On the other hand, an estimate of f_d might be used to estimate velocity.

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Figure 1 - Relative Errors